NASA Ka-Band Transition Systems - Capabilities and Demonstrations for Near-Earth Communications Services

Dave Zillig, Diep Nguyen
NASA/Goddard Space Flight Center, Greenbelt, MD 20771
Tel: (301) 286-8003/1410; Fax: (301) 286-1724; E-mail: david.j.zillig.1@gsfc.nasa.gov

Mark Burns, James Brase
ITT Advanced Engineering & Sciences Division, 1761 Business Center Drive, Reston, VA 20190
Tel: (703) 438-8155; Fax: (703) 438-8112; E-mail: mark.burns@itt.com

1. Introduction

Due to continued and increasing congestion in the S-, X-, and Ku-band frequency spectrums and ever-increasing demand for higher data rate transmissions by United States' National Aeronautics and Space Administration (NASA) spacecraft, it has become necessary to explore the use of higher radio frequency spectrum for NASA space-to-ground communications requirements. The available spectrum is a finite resource, and as the data throughput requirements from space-to-ground increase beyond the available X and Ku-band spectrum, it will become necessary for NASA low earth orbiting (LEO) spacecraft to transition to the allocated Ka-Band spectrum for space-to-ground communications links.

Starting in 2000, NASA/Goddard Space Flight Center (GSFC) launched the first of three new spacecraft, known as Tracking and Data Relay Satellite (TDRS) H,I,J to complete the Space Network's (SN) next generation of tracking and data relay satellites used to support LEO spacecraft. TDRS H,I,J will maintain compatibility with existing user spacecraft at S- and Ku-bands while adding a Ka-band space-to-space link communications capability. The TDRS H,I,J Ka-band space-to-space links will operate in bands allocated on a primary basis to Inter-Satellite Service (ISS). NASA currently operates in a Ku-band for space-to-space links that is allocated on a secondary basis, and therefore may be subject to operational restrictions in the future. The Ka-band space-to-space forward link will operate in the 22.55 GHz to 23.55 GHz band, with the return link from the user spacecraft to TDRS H,I,J tunable across the 25.25 to 27.5 GHz band and a channel bandwidth up to 650 MHz. The TDRS space-to-ground links will continue to operate at Ku-band. The 1997 World Radiocommunication Conference (WRC-97) allocated the band 25.5-27.0 GHz to the Earth exploration-satellite (EES) service (space-to-Earth) [1]. This allocation enables the direct transmission of environmental observations and measurements from Earth-orbiting satellites to earth stations. NASA current uses its Ground Network (GN) to support direct transmissions from LEO spacecraft, however, it is limited to operation primarily at S-band an X-band.

To take full advantage of the allocated Ka-band spectrum and TDRS H,I,J Ka-band capabilities within the NASA SN, enhancements to the ground station equipment at the White Sands Complex (WSC) will be required. Likewise, Ka-band enhancements to the GN will be required to support direct-to-ground links.

The NASA/GSFC Mission Services Program Office seeks to evolve interoperable Ka-Band data services for the SN and GN to support the transition of NASA LEO users to Ka-Band. In early 2000, NASA/GSFC established the Ka-Band Transition Project (KaTP) to develop and implement the necessary network infrastructure for demonstrating interoperable SN and GN Ka-band data services. The project will is currently implementing a new Ka-band ground station for the GN and modifying the SN ground stations at the WSC to provide compatible IF outputs that will be used for high data rate demonstrations. When the implementation is complete in mid 2002, high data rate demonstrations ($\geq$ 600 Mbps) will performed through the use of high data rate receivers and a LEO spacecraft simulator. The project will provide the results and impetus to guide the future direction for Ka-band data service provisioning.

2. Drivers for Ka-Band Operations

NASA's Space Network (SN) currently provides communications support at S-band and Ku-band to a variety of flight projects via the Tracking and Data Relay Satellite System (TDRSS) and ground assets located at the WSC. Similarly, NASA's GN provides communications support at S-band and X-band to flight projects via direct links to ground stations located worldwide. NASA's forecasts for Earth exploration-satellite sensors indicate future missions will require data rates up to 1Gbps necessitating bandwidths as high as 400-800 MHz. Theses escalating user data throughput requirements cannot be supported by the present X-band spectrum. Additionally, NASA's allocations for the TDRSS Ku-band forward and return links are secondary through the NTIA and ITU. There will likely be increasing interference to the TDRSS forward links from Fixed Satellite Service Earth stations transmitting in the Earth-to-space direction. As a result, NTIA and the DoD have urged NASA to vacate Ku-band.

The NASA Ka-band spectrum has primary allocation from the NTIA and ITU for both Inter-Satellite Service (ISS) and EES service as shown in Table 1. NASA's next generation TDRSS satellites (TDRS H,I,J) will support Ka-band forward and return links in the ISS allocation. These links offer frequency agility (i.e., forward link is tunable in 5 MHz steps within a 1 GHz band, return link is tunable in 25 MHz steps within a 2.25 GHz band); and the return link bandwidth of 650 MHz can support user data rates of 800 Mbps or higher. Also, because of the overlap of the ISS and EESS Ka-band allocations (25.5 to 27.0 GHz), LEO spacecraft can be designed to downlink high rate data either directly to a ground station or through TDRS H,I,J. This provides users with additional flexibility for both normal operations and contingencies. Other advantages of Ka-band include narrower beamwidths, which reduces the susceptibility to interference, reduced size and mass of the user hardware (especially the antenna), and a higher antenna G/T and system EIRP than the current TDRSS Ku- and S-band links.

Table 1. Ka-Band Spectrum Allocations Available to NASA/GSFC Missions

Band	Ground Network		Space Network	
	Link/Frequency	Allocated Services	Link/Frequency	Allocated Services
Ka-Band	**Earth-to-Space (Uplink):** N/A	**No Allocation**	**Space-to-Space (Forward Link):** 22.55 – 23.55 GHz	**Primary**: Inter-Satellite
	Space-to-Earth (Downlink): 25.5 – 27.0 GHz	**Primary**: Earth Exploration-Satellite	**Space-to-Space (Return Link):** 25.25 – 27.5 GHz	**Primary**: Inter-Satellite

3. Ka-Band Transition Project Overview

The KaTP is a GSFC technology development, integration, and demonstration initiative to facilitate the transition of high data rate SN and GN user spacecraft to the NASA-allocated Ka-band frequencies. NASA/GSFC's approach for demonstrating the SN and GN Ka-band capabilities is to leverage in-house technology development and utilize commercial equipment vendors to provide products that operate within the NASA allocated Ka-band frequencies.

The net result of this project will be common Intermediate Frequency (IF) services within the SN and GN, and high data rate demonstrations that use the IF service in conjunction with test receivers and transmitters to demonstrate support of Ka-Band LEO spacecraft at rates up to at least 600 Mbps. The project conducted a system design review in December 2000 and is currently performing hardware acquisition and integration activities. GN acceptance testing is scheduled for the November 2001 timeframe and the April 2002 timeframe for the SN. The high data rate SN and GN demonstrations are presently scheduled for the fall of 2002.

3.1 Space Network Implementation

The SN ground stations at the WSC (New Mexico, USA) will be upgraded to take advantage of the new TDRS H,I,J spacecraft 650 MHz-wide Ka-band space-to-space return link in the 25.25 GHz band to 27.5 GHz band. The WSC ground stations are presently capable of supporting Ka-band users via TDRS H,I,J at data rates up to 300 Mbps. Figure 1 illustrates the modifications and additions that will be performed to the WSC Space-Ground Link Terminals (SGLTs) as part of the KaTP. Table 2 lists the key parameters of the SN 650 MHz-wide Ka-band capability provided by the KaTP.

A prime and redundant 650 MHZ-wide IF service will be implemented at four of the five SGLTs by adding new downconverts and waveguide equalizers. The downconverters will receive the 650 MHz-wide Ku-band downlink signal from TDRS H,I,J spacecraft and output a 1200 MHz IF signal. The IF signals will be fed into an IF switch for routing to a user supplied high data rate receiver. The equalizer will correct for phase and amplitude distortions that result when wide band signals propagate through long waveguide runs.

Also, the existing 225 MHz-wide prime and redundant downconverters will be modified to support dual Ka-band frequency plans. The two plans supported will be the TDRS H,I,J frequency plan and the Space Networks Interoperability Panel (SNIP) frequency plan [2]. Additionally, software and firmware at WSC will be modified to support the scheduling, control, and monitoring the new and modified hardware.

3.2 Ground Network Implementation

A single GN station will be installed at NASA’s Wallops Flight Facility (WFF) in Virginia, USA to support unified S-Band command (2025 to 2120 MHz) and telemetry (2200 to 2300 MHz), and Ka-Band telemetry (25.5 to 27.0 GHz). Figure 2 is a block diagram of the KaTP GN ground station and Table 3 lists some of the key parameters of the Ka-band receive system.

The station will consist of 5.4 meter X-Y mount antenna housed in radome with a Ka-band cassegrain feed and an S-band prime focus feed. The Ka-band ground station equipment will provide an IF output at 1200 MHz with an interface identical to the SN Ka-band IF output. The station will support simultaneous Ka-Band and S-band telemetry receive, S-band command transmit, and S-band and Ka-band antenna autotrack. The ground station is intended to be used only for demonstration purposes and therefore station automation will be limited to monitor and control of the antenna subsystem.

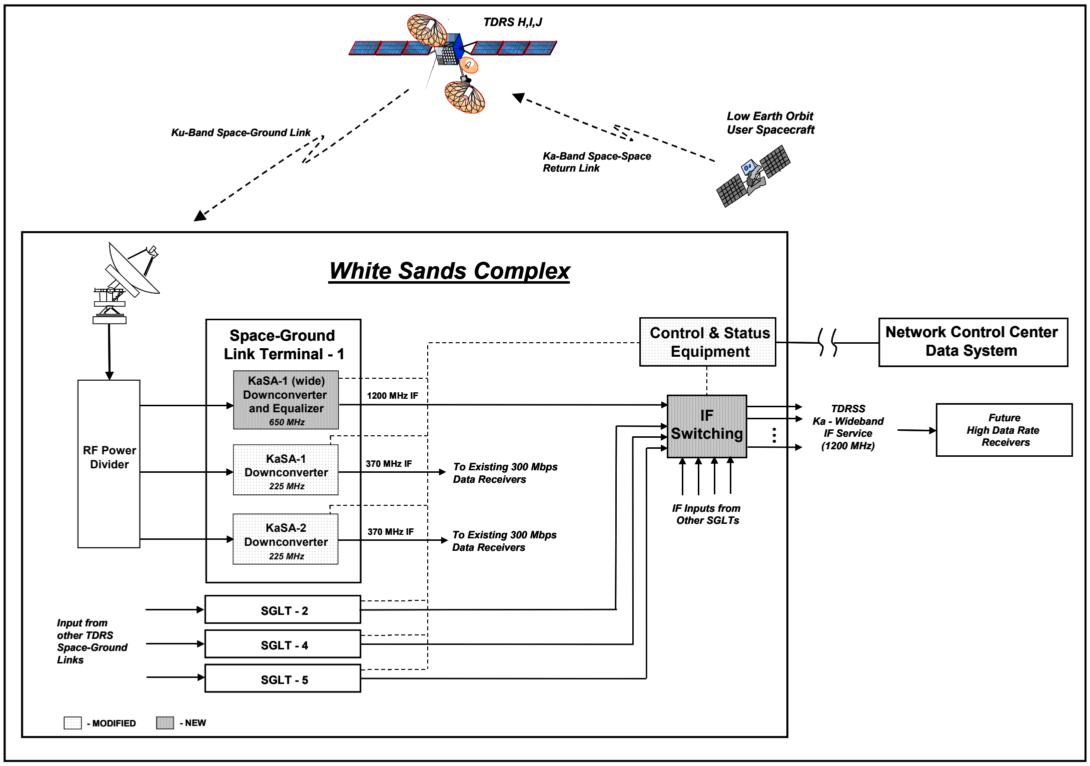

Figure 1. SN Ka-Band (650 MHz-wide) Reference Architecture

Table 2. Key Parameters for the SN Ka-Band 650 MHz-wide Service

Parameter	Requirement
1. Frequency Range	25.25 to 27.5 GHz
2. TDRS Antenna G/T	26.5 dB/K, autotrack mode
3. TDRS Antenna Axial Ratio	1.0 dB maximum
4. Polarization	RHC or LHC; selectable
5. RF Channel 3 dB Bandwidth	650 MHz
6. RF Channel Tuning	SNIP Frequency Plan
7. IF Output Center Frequency	1200 MHz
8. Gain Flatness	≤ 0.9 dB p-p over ±230 MHz about IF
9. Phase Nonlinearity	≤ 30 degrees p-p over ±230 MHz about IF
10. Noise figure	≤ 15 dB

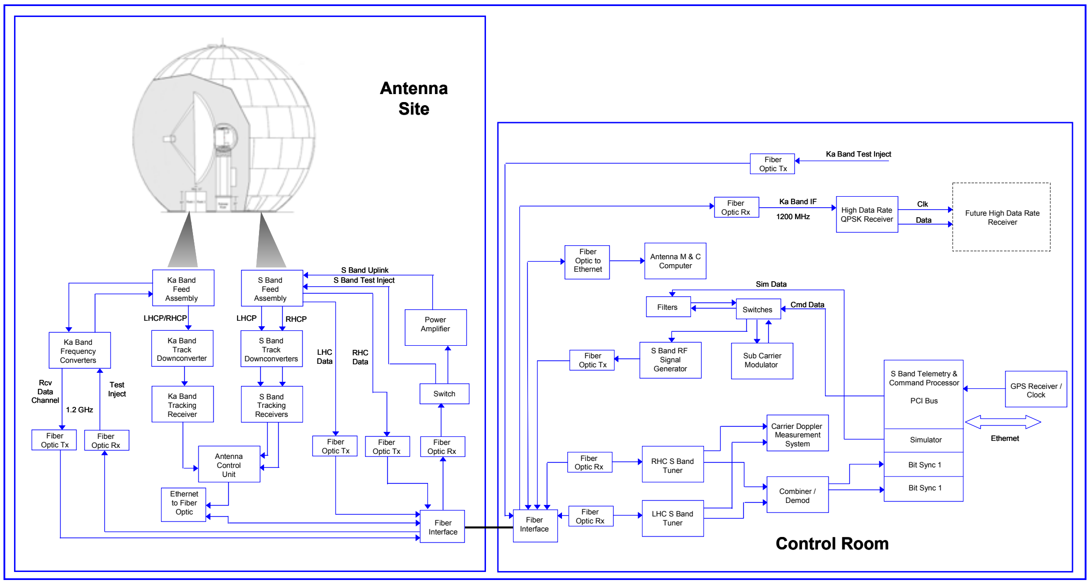

Figure 2. GN Ka-Band Ground Station Block Diagram

Table 3. GN Ka-Band Ground Station Key Parameters

Parameter	Requirement
1. Frequency Range	25.5 to 27.0 GHz
2. Antenna G/T	32.5 dB/K; clear sky, 10 degrees elevation
3. Axial Ratio	2.0 dB maximum
4. Polarization	RHC or LHC; selectable
5. Radial Tracking Error	0.05 degrees; 1 sigma
6. RF Channel 3 dB Bandwidth	1200 MHz
7. IF Output Center Frequency	1200 MHz
8. Tuning Step Size	125 kHz
9. Gain Flatness	≤ 2.0 dB p-p over ±525 MHz about IF
10. Phase Nonlinearity	≤ 10 degrees p-p over ±525 MHz about IF
11. Noise figure	≤ 16 dB

3.3 High Data Rate Demonstration

The KaTP high data rate demonstration will utilize the new equipment implemented within the SN and the new ground station implemented within the GN to show that the networks can support LEO spacecraft with data rates up to 600 Mbps in the 25.25 GHz to 27.5 GHz band. The high rate equipment (receivers) required for the Ka-band demonstration are fundamentally equivalent for both the SN and GN due to the common IF interface design in both networks. The main objectives of the KaTP demonstration are to:

1. Characterize the performance of the physical return links at data rates up to 600 Mbps
   a. GN: Direct-to-earth Ka-band downlink
   b. SN: return Ka-band link relayed via TDRS H
2. Characterize the acquisition and tracking performance of the GN Ka-band antenna
3. Assess the effects of hardware distortion on the overall link

4. Characterize the GN and SN system designs
5. Provide an end-to-end system for characterizing the capabilities of new spacecraft Ka-band and high-data-rate hardware

The demonstration will assess the RF link performance via measurements of implementation losses and the signal spectra. These measurements will be performed at various data rates and simulated spacecraft EIRPs. For the GN, antenna autotrack acquisition of a moving source will also be demonstrated.

Figure 3 and Figure 4 are high-level block diagrams of the SN and GN demonstration configurations, respectively. A high-rate data transmitter will provide the Ka-band signal source for the demonstration. The SN demonstration will use the TDRS H spacecraft to relay the signal to an SGLT at the WSC. The SN demonstrations will utilize on-site test equipment including the existing KaSA Test Antenna System to simulate a high rate Ka-band Single Access Return (KaSAR) user. The GN will utilize a boresite antenna in conjunction with a high rate signal source for bit error rate (BER) testing, and a NASA aircraft will be used for antenna acquisition and tracking tests. The KaTP project will also investigate the use of potential targets of opportunity such as the ENVISAT spacecraft for the Ka-band demonstrations.

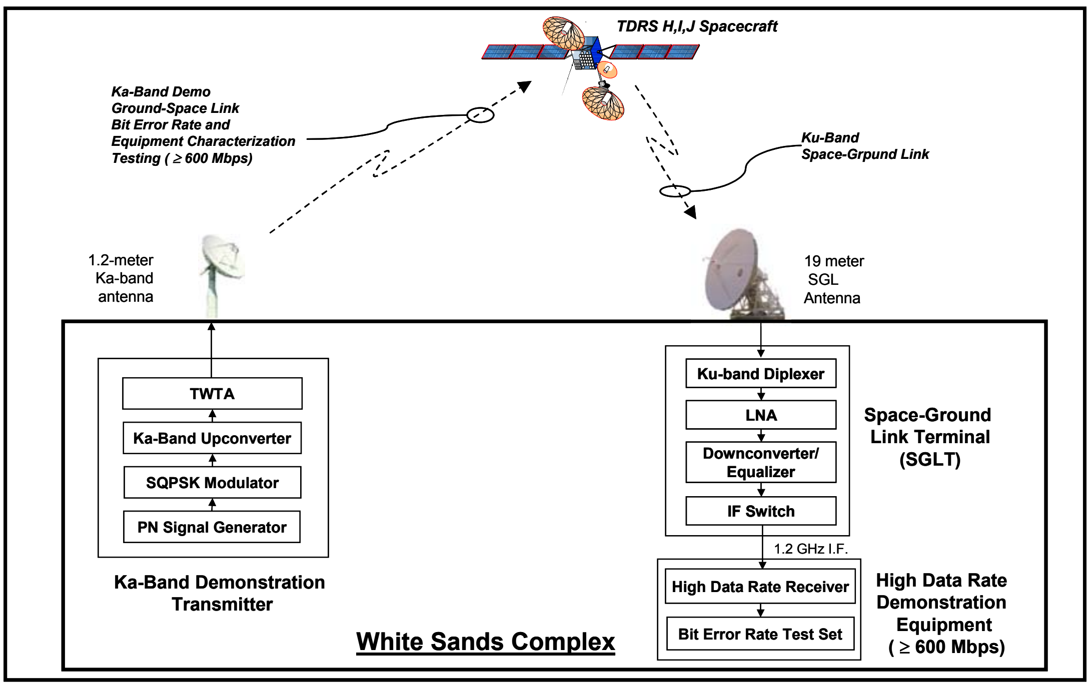

Figure 3. SN Demonstration Configuration

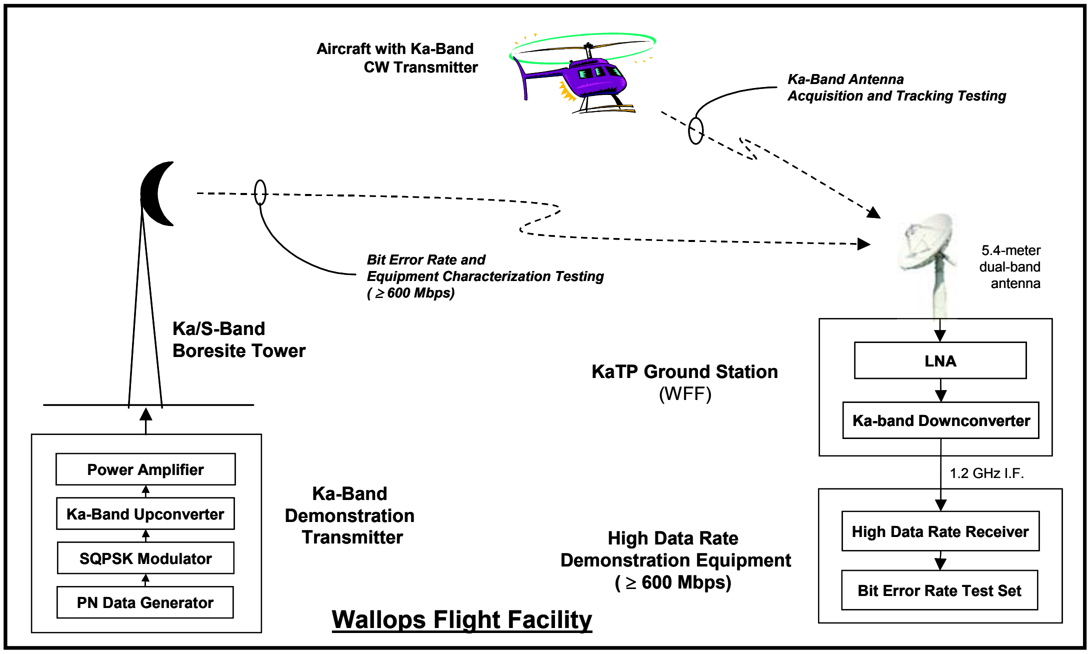

Figure 4. GN Demonstration Configuration

3.4 System Performance Simulations

As part of the requirements analysis and system design process for the KaTP SN and GN implementations, end-to-end system engineering analyses were performed using analytical and simulation techniques. These analyses were used to derive the Ka-band user tranmitter distortion requirements and to predict the implementation loss associated with a TDRSS user operating at various data rates and modulation schemes. Analyses were performed primarily for SN Ka-band users since this link induces the most loss due to TDRS transponder distortions, atmospheric effects, and path loss. SPW simulations were used to predict the end-to-end link implementation loss due to transmitter, TDRS transponder, and ground station linear/non-linear distortions. The implementation loss were then used in link budgets to determine feasibility and link margin.

Table 4 is a summary of the implementation loss analyses performed for the SN link. Even though the KaTP demonstrations will be performed using OQPSK modulation at 600 Mbps, analyses were also performed for other higher order modulation schemes at data rates up to 1 Gbps to help characterize the channel. Implementation losses for the direct-to-ground GN links would be slightly less than those shown in the table due to the elimination of the TDRS transponder distortion effects. Simulation methods were used to determine the impact of data rise time, bandlimiting, gain flatness, gain slope, phase nonlinearity, AM/AM, AM/PM, incidental AM, spurious outputs, spurious PM and phase noise. Analytical methods were used to determine the impact of gain imbalance, phase imbalance, data asymmetry, I/Q data skew and data bit jitter. The total implementation loss due to all distortions was computed by adding the contribution found via simulation to the contribution found analytically.

Table 4. Link Performance for SN Ka-Band High Data Rate Service

Communication Scenario		Ground Terminal Description			Implementation Loss(1, 2, 3)
Modulation/ Coding	Data Rate	Phase Nonlin Shape	Detection Method	Baseband Equalizer	
QPSK Uncoded	600 Mb/sec	Random 1	Butterworth Filter(4)	No	3.53 dB

QPSK Uncoded	600 Mb/sec	Random 1	Butterworth Filter(4)	Yes	2.36 dB
QPSK Uncoded	800 Mb/sec	Random 1	Butterworth Filter(4)	No	4.95 dB
QPSK Uncoded	800 Mb/sec	Random 1	Butterworth Filter(4)	Yes	2.30 dB
GMSK (BT_s = 1)	800 Mb/sec	Random 1	Butterworth Filter(4)	No	4.22 dB
8PSK Uncoded	800 Mb/sec	Random 1	Butterworth Filter(4)	Yes	≈ 5.83 dB
8PSK/TCM (8-state)	800 Mb/sec	Random 1	Butterworth Filter(4)	No	2.66 dB
8PSK/TCM (8-state)	800 Mb/sec	Random 1	Butterworth Filter(4)	Yes	1.57 dB
8PSK/TCM (8-state)	1 Gb/sec	Random 1	Butterworth Filter(4)	No	≈ 8.00 dB
8PSK/TCM (8-state)	1 Gb/sec	Random 1	Butterworth Filter(4)	Yes	2.79 dB

Notes:

1. At 10^{-5} BER and relative to the theoretical performance of the particular modulation scheme being analyzed. QPSK theoretical BER performance crosses 10^{-5} BER at Eb/No = 9.6 dB. 8PSK theoretical BER performance crosses 10^{-5} BER at Eb/No = 13.18 dB. 8PSK/TCM (monodimensional) theoretical BER performance crosses 10^{-5} BER at Eb/No = 7.12 dB for 4 states and 6.82 for 8 states. GMSK (BT_s = 1) theoretical BER performance crosses 10^{-5} BER at Eb/No ≈ 10.4 dB.
2. Values determined using a combination of analytical and simulation methods. For 8PSK, 8PSK/TCM and GMSK, all distortions simulated with the exception of user gain imbalance, phase imbalance, I/Q data skew, data asymmetry, data bit jitter and frequency instability which were addressed analytically. For QPSK, all distortions simulated with the exception of user data bit jitter, user frequency instability and system phase noise which were addressed analytically.
3. For 800 Mb/sec 8PSK/TCM, the 95% confidence interval is approximately ±0.25 dB. For 1 Gb/sec 8PSK/TCM, the 95% confidence interval is approximately ±0.45 dB. For GMSK, the 95% confidence interval is approximately ±0.3 dB.
4. Third order Butterworth filter of bandwidth 0.55 x symbol rate. A sample-and-hold was used after the filter.

4. Enabling Technology Developments within NASA

REFERENCES

[1] B. Younes, et al, “ITU-R Studies of Sharing Between Space Systems and Terrestrial Systems in the 25.25-27.5 GHz Band,” Proceedings of the Seventh Ka-Band Utilization Conference, Santa Margherita Ligure, Italy, September 26-28, 2001.

[2] “Recommendations for International Space Network Ka-Band Interoperability,” ESA/NASA/NASDA Space Networks Interoperability Panel, Revision 1, dated June 1995.